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COMBUSTION CHARACTERISTICS IN THE TRANSITION REGION OF LIQUID FUEL SPRAYS

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ABSTRACT

A number of important effects have been observed in the droplet size transition region in spray combustion systems. In this region, where the mechanism of flame propagation is transformed from diffusive to premixed dominated combustion, the following effects have been observed: (1) maxima in burning velocity; (2) extension of flammability limits; (3) minima in ignition energy; and (4) minima in NO_x formation. Unfortunately, because of differences in experimental facilities and limitations in the ranges of experimental data, a unified description of these transition region effects is not available at this time. Consequentl· a fundamental experimental investigation was initiated in January, 1983 to study the effect of droplet size, size distribution, and operating parameters on these transition region phenomena in a single well controlled spray combustion facility.

A monodisperse aerosol generator is used to form and deliver a well controlled liquid fuel spray to the combustion test section where measurements of ignition energy, flammability limits, and flame speeds are to be made. Optical in-situ particle sizing of fuel droplets will be used to characterize the droplet size distribution, number density, and extent of vaporization at the test section. These studies are expected to lead to a comprehensive understanding and explanation of spray combustion transition region effects.

In the first year of the project, work has concentrated on the design and construction of the ignition and droplet sizing systems. An existing spray burner facility has also been modified to accommodate the

present experiments. Preliminary testing of the new burner facility and the droplet ignition system has been carried out. Parametric studies of the effects of droplet size, equivalence ratio, droplet number density, prevaporization, flow velocity, and fuel and oxidizer composition on minimum ignition energy will begin shortly. A similar evaluation of the effects of these parameters upon flammability limits and flame speed will follow.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

COMBUSTION CHARACTERISTICS

IN THE TRANSITION REGION OF LIQUID FUEL SPRAYS

I. INTRODUCTION

The combustion of liquid fuel sprays is currently responsible for a large portion of the total energy consumption of the world. For example, 36.4% of U.S. consumption of fossil energy in 1981 was in the form of jet distillate and residual fuels which were consumed in burning sprays (Gustaferro, 1982). In order to improve combustion efficiency and to predict and control pollutant formation in practical systems, a detailed understanding of the combustion phenomena is required. A number of significant studies have been carried out in the so called transition region, where the relative roles of heterogeneous and homogeneous effects in dominating the combustion processes are switched. In this transition region, it has been shown that the mechanism of flame propagation is completely transformed from diffusive to premixed dominated combustion (Burgoyne and Cohen, 1954). The following important effects also have been observed in the transition region:

(1) Maxima in burning velocity

(2) Extension of the lean flammability limits;

(3) Minima in ignition energy; and

(4) Minima in NO_x formation

However, due to the very different aerosol generation techniques (generally poorly controlled polydisperse sprays), limited and dissimilar operating ranges (e.g. equivalence ratio), different combustion systems, etc. used by the various investigators, a consolidated picture

of these transition region phenomena and their mechanisms is not yet available. Thus, there is a need for comprehensive studies examining these effects in more detail, particularly where better control can be placed on the experimental variables.

A fundamental study was initiated in January 1983, making use of an existing liquid spray combustion facility, to isolate and explain the true droplet size effects and optimum droplet diameters corresponding to (1) maximum burning velocity, (2) minimum ignition energy, and (3) maximum extension of the flammability limits. The use of a single spray combustion facility for all of this work insures uniformity in the interpretation of data and is expected to lead to the formulation of a comprehensive model of combustion in the transition region. This program follows the recently completed study of Cernansky and Sarv (1983) on NO_x formation in monodisperse fuel spray combustion.

The experimental program plan has the following specific objectives:

(1) To map the minimum ignition energy for a monodisperse fuel spray combustion system in the transition region (10 - 80 μm initial droplet diameter) for various fuels of interest and for other important variables such as equivalence ratio, flow velocities, and fuel type;

(2) To determine the optimum droplet diameter at which the ignition energy is minimized;

(3) To study the effects of changing the evaporation environment on the minimum ignition energy;

(4) To characterize the ignition requirements of polydisperse fuel sprays in terms of the droplet size distribution; and

(5) To determine the effects of droplet size and size distribution on flame speed.

In the first year of the project the design, purchase, and construction of a new droplet ignition system and a new droplet sizing system were completed and the existing burner arrangement was modified. The spray burner has been changed from a vertically upward orientation to a vertically downward configuration in order to prevent fuel accumulation in the test section. The flow geometry has also been changed to prevent flashback in the new configuration. The burner system now accommodates an ignition system which allows the control and measurement of ignition energy. Also, in situ optical diagnostics of droplet size and velocity measurements are being introduced to the facility.

The efforts in the first six months of the program were reported in the first interim progress report dated August 1983. This report is intended to briefly summarize the progress over the first year of the program, with emphasis on the past six-month period.

II. RESEARCH PROGRAM

A. Program Overview

An overview of the research program including major tasks, subtasks and schedules is presented in Table 1. Task 1 is intended to upgrade the existing spray combustion facility in order to accomplish the research objectives mentioned in Section I. Task 2 is intended to develop an understanding of the effects of droplet size and size distribution and other important operating parameters on minimum ignition energy requirements and flammability limits for fuel sprays in the transition region. Task 3 is intended to determine the effects of these variables on flame speeds in the same region of interest. A unified description of the characteristics exhibited by transition region fuel sprays is thus expected to result from the research program. The following sections discuss the efforts made in the first year of the program in the areas of facilities and equipment improvements (Task 1) and ignition studies (Task 2).

B. Research Progress

The main areas of progress to date have been in the design and fabrication of the ignition system and the optical droplet sizing diagnostics. At this point, the design and construction of each of these systems is complete. The details of the designs of both systems were presented in the previous interim progress report. A digital data acquisition system consisting of a digital oscilloscope and an LSI-11 based minicomputer is currently being incorporated into the facility.

In addition to the above work, in the past six months the spray burner facility has been converted from an upward flowing configuration to a downward arrangement. This was done in order to prevent accumulation

Table 1. Program Plan and Schedule

Task	Year 1	Year 2	Year 3
TASK 1. FACILITIES AND EQUIPMENT IMPROVEMENTS	XXXXXXXXXXX	XXX	
A. Modify Monodisperse Combustion Facility for Ignition Studies	————[X-	--]	
1. Design and Fabricate Ignition System	——X-----]		
2. Interface LDA System	——[-X---	--]	
3. Interface Data Acquisition System	——[X-	--]	
B. Develop Diagnostics for Droplet Size and Velocity Distributions	[---————	——X	
1. Data Acquisition Software	———X		
2. Data Reduction Software	——	——X	
3. Develop Droplet Sizing System	[---————	——X	
TASK 2 IGNITION STUDIES	XXX	XXXXXXXXXXX	XXXXX
A. Exploratory Measurements	——	———X	
1. Test Ignition Behavior at Selected Operating Conditions	——	X-]	
2. In Situ Droplet Sizing and Characterization		———X	
B. Parametric Studies of Ignition Behavior		————————	———X
1. Droplet Size and Equivalence Ratio Effects		——[X--]	
2. Number Density and Prevaporization Effects		—————X	
3. Air Velocity and Composition Effects		———	———X
TASK 3. FLAME SPEED STUDIES			XXXXXXXXXXX
A. System Setup and Exploratory Measurements			——X
B. Parametric Studies of Flame Speed Behavior			—————X

————————X As Originally Proposed
[---------] Revised Plan

of fuel droplets in the test section. Exploratory tests have been conducted with the new burner configuration and the new ignition system and the results are discussed below.

1. Development of Spray Combustion Facility

A Berglund-Liu vibrating orifice aerosol generator is used to supply a well-defined and characterized spray of monodisperse droplets to a test section for ignition and flammability limit studies or for flame speed studies. In this system, droplet size, number density, stoichiometry, fuel type and properties, and extent of prevaporization can be independently varied and their effects isolated and studied. Droplet diameters can be routinely varied between 10-80 μm with a standard deviation of less than 1% of the mean.

After generation, the droplets are subjected to a flow of dispersion air to prevent coagulation. The aerosol then passes through a flow reducing section where dilution air is added to achieve the desired stoichiometry. Both the dispersion and dilution air flows are adjusted and monitored by electronic flow controllers. Thus, the equivalence ratio can be varied over the entire range of flammability. Fuels as diverse as n-heptane, methanol, n-octane, tetralin, kerosine, and others can all be used in the system. Evaporation characteristics can be changed by fuel selection (to affect molecular weight, boiling point, latent heat, C/H ratio, etc.), by altering the oxidizer composition (e.g., He or Ar addition or substitution), or by heating the dilution and dispersion air flows.

The aerosol generator and the combustion test section are mounted on a three dimensional traversing mechanism to enable scans of the entire flow field. This mechanism may be automated to enable positioning or traversing under computer control.

After careful consideration of the present experimental requirements a downward flowing spray orientation was chosen over the former upward flowing arrangement in order to prevent accumulation of fuel droplets in the test section. This provides for better uniformity of the spray, smaller differences between droplet and air flow velocities and an added margin of safety. A schematic of the modified spray burner facility is presented in Figure 1.

The design of the flow reducing section was also changed in order to provide flow velocities which would always exceed the flame speed thereby preventing flashback. Special consideration was given to maintaining uniform flow as well since a screen flameholder, such as that used in previous NO_x emission experiments, was not appropriate for use in the present experiments. Measurements discussed in the previous progress report indicated that only about 30% of the drops survive through the screen. While not a major concern in the previous NO_x emissions study (Cernansky and Sarv, 1983) in which a steady flame immediately vaporized all droplets impacting on the screen, this accumulation of droplets would have significantly affected the stoichiometry and evaporation environment in the present ignition/flammability limit tests where a steady flame is not produced in the test section. Initial tests have shown that the present spray apparatus achieves a uniform aerosol flow with virtually no fuel droplet accumulation in the test section. Preliminary tests have also shown that for the flame speed measurements a stable flame can still be produced by the modified burner system over a wide range of fuel and air flows with no tendency for flashback to occur.

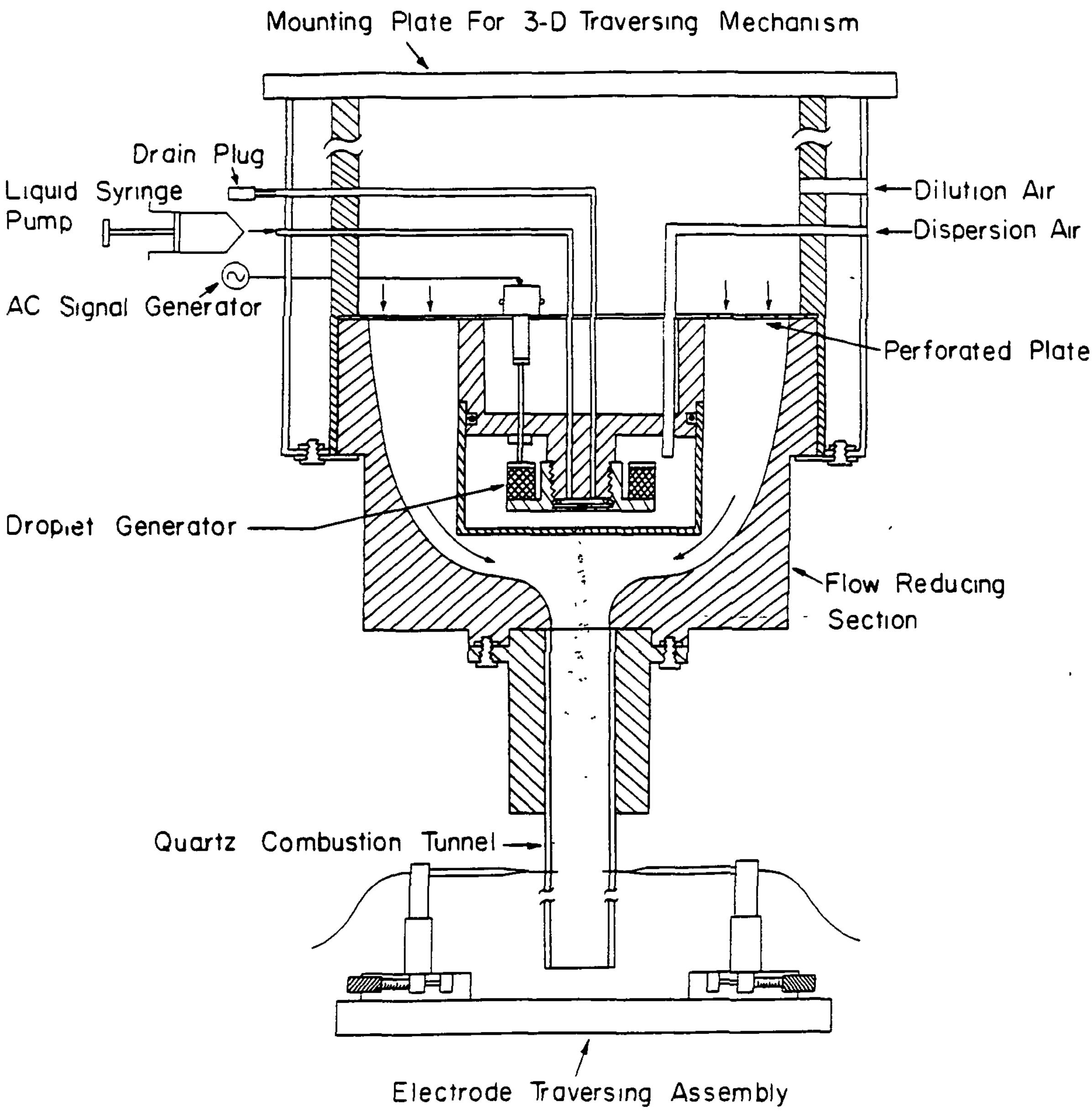

Figure 1. Schematic of the Spray Burner Facility

2. Ignition System

In order to determine the minimum energy needed to ignite a combustible mixture, an electric spark of variable duration and energy is desirable. The test section has been fitted with a set of ignition electrodes, which can be adjusted for gap spacing, position in the fuel spray, geometry, etc. Energy for ignition is provided using an adjustable spark discharge.

Briefly, the ignition system follows the design of Peters (1981) with a few additional features added for improved safety of operation. A schematic of the system is shown in Figure 2. The capacitative discharge ignition circuit has the capability of varying power by varying capacitance and resistance. These values can be varied independently by using switches to connect or disconnect capacitors or resistors from their respective banks. A micrometer traversing assembly is used to adjust the distance between the stainless steel primary electrodes, thus varying the energy density of the spark. The capacitors are charged to 30 KV by a high voltage source which is then disconnected from the circuit before ignition. The auxiliary spark gap (AS) is set so that the breakdown voltage (voltage required for a spark to bridge the gap) is slightly larger than the breakdown voltage in the primary spark gap (PS). When the triggering switch (S_t) is opened a small spark is generated at the AS, lowering its breakdown voltage so that the voltage across the AS exceeds the breakdown voltage. When the spark jumps across AS, a large voltage difference forms across PS and a spark is generated.

To measure the voltage of that spark, a high voltage probe is connected across the electrodes (i.e., across PS) and a voltage trace of the spark is recorded on one channel of a Norland two-channel digital oscilloscope.

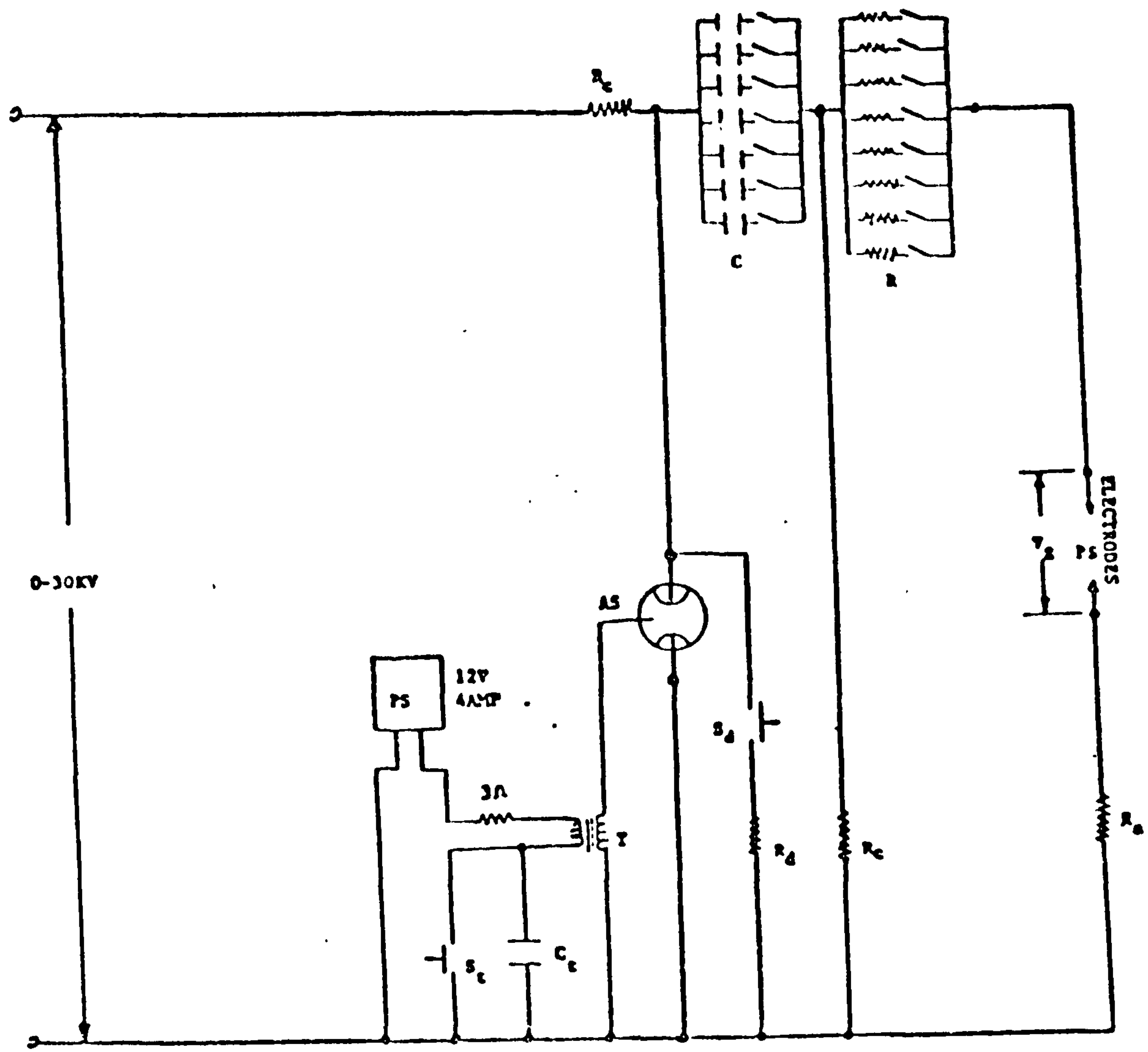

FIGURE 2 SCHEMATIC OF IGNITION SYSTEM

The voltage across R_s, is recorded on the second channel to determine the current in the primary spark. The energy of the spark, E, is determined from $E = \int_0^t V(\tau)I(\tau)d\tau$ where V is the measured voltage across the electrodes, I is the R_s, and τ is time. The waveform processing capability of the digital oscilloscope provides rapid evaluation of the above expression.

The spark has successfully ignited the aerosol in preliminary tests, however, difficulties have been encountered in generating reproducible spark energies. The design of the ignition system is being modified slightly to improve its repeatability. Upon obtaining satisfactory performance from this system, optimum spark gaps for minimum ignition energies at selected burner operating conditions will be determined. Once these values are known, the parametric studies of ignition behavior will begin.

3. Droplet Sizing and LDA Systems

For the flame speed studies, a flame will be stabilized at a point or line in the test section, resulting in a steady oblique flame. The flame speed is then given as the flow velocity component which is normal to the flame surface just upstream of the flame. The flame surface can be defined by either direct observation or photographs, or by identifying the isotherm which corresponds to a 10% increase in temperature over the incoming stream (Smith and Gouldin, 1977).

Flow and drop velocities will be obtained using laser Doppler anemometry (LDA) (Drain, 1980). A Thermo Systems Incorporated (TSI) LDA utilizing a 35 milliwatt He-Ne laser and a TSI Model 1980 counter will be used to characterize the velocities in fuel sprays and for flame speed measurements.

An apparatus has been designed which will provide the capability for measuring droplet size and size distribution in both the minimum ignition energy/flammability limit and the flame speed experiments. The sizing diagnostic is similar to the Mie scattering technique developed and reported by Yule *et al.* (1977), Ungut *et al.* (1978), Holve and Self (1979), and Holve (1980) to obtain the size distribution of the spray droplets. The technique is based on the measurement of the peak of the scattered light intensity as a particle crosses the laser probe volume. Since the illumination is Gaussian (TEM_{00}), the scattered light depends on both particle size and where it crosses the probe volume. Therefore, a second gate detector will be used to ensure that the droplets which are sized all cross through the center of the laser beam.

An advantage of the sizing method chosen is that it enables one to greatly simplify the data acquisition and processing apparatus required by other in-situ sizing techniques, e.g., visibility method. It is a non-intrusive technique capable of measuring droplet sizes in the 10 - 100 μm range with a minimal dependence on index of refraction. The development of the design was discussed in detail in the previous progress report. The development of the data acquisition software and the integration of the laser and optical bench into the modified burner facility are currently in progress.

The droplet size measuring system consists of a 35 mW He-Ne laser (632.8 nm wavelength), transmitting optics, and light collection optics which focuses the scattered light onto a photomultiplier tube. A second detector system is used to gate the signal from the primary detector. A schematic of the optical setup is shown in Figure 3. The transmission optics consists of a 19 mm focal length cylindrical lens followed by a 250 mm focal length spherical lens. When the laser beam passes through this lens system a ribbon beam is produced which has a cross-section of about 100 μm X 1 cm at the focal plane of the spherical lens. When the spray passes through the focussed beam, it scatters the laser light. The near-forward scattered light is collected by the primary detector optics. This consists of a 55 mm f/1.4 camera lens, a pinhole for spatial filtering, and a 10 nm bandwidth laser interference filter. The light is measured using a RCA 4840 photomultiplier tube. The gate detector system collects light scattered at 90°. For maximum flexibility, the gate detector system contains the same components as the primary detection system. Both detector systems are mounted on precision translation and rotation stages to allow extremely accurate positioning and alignment of the optical system.

The signal processing system for the droplet sizing apparatus is shown in Figure 4. When a fuel droplet passes through the probe volume, defined by the intersection of the laser beam and the collecting optics field of view, nearly simultaneous Gaussian-type current pulses are produced by each of the photomultiplier tubes. Each of these pulses is processed on a single channel analyzer (SCA). When the signal peak occurs each SCA sends a TTL-logic pulse to an adjustable one shot chip which then

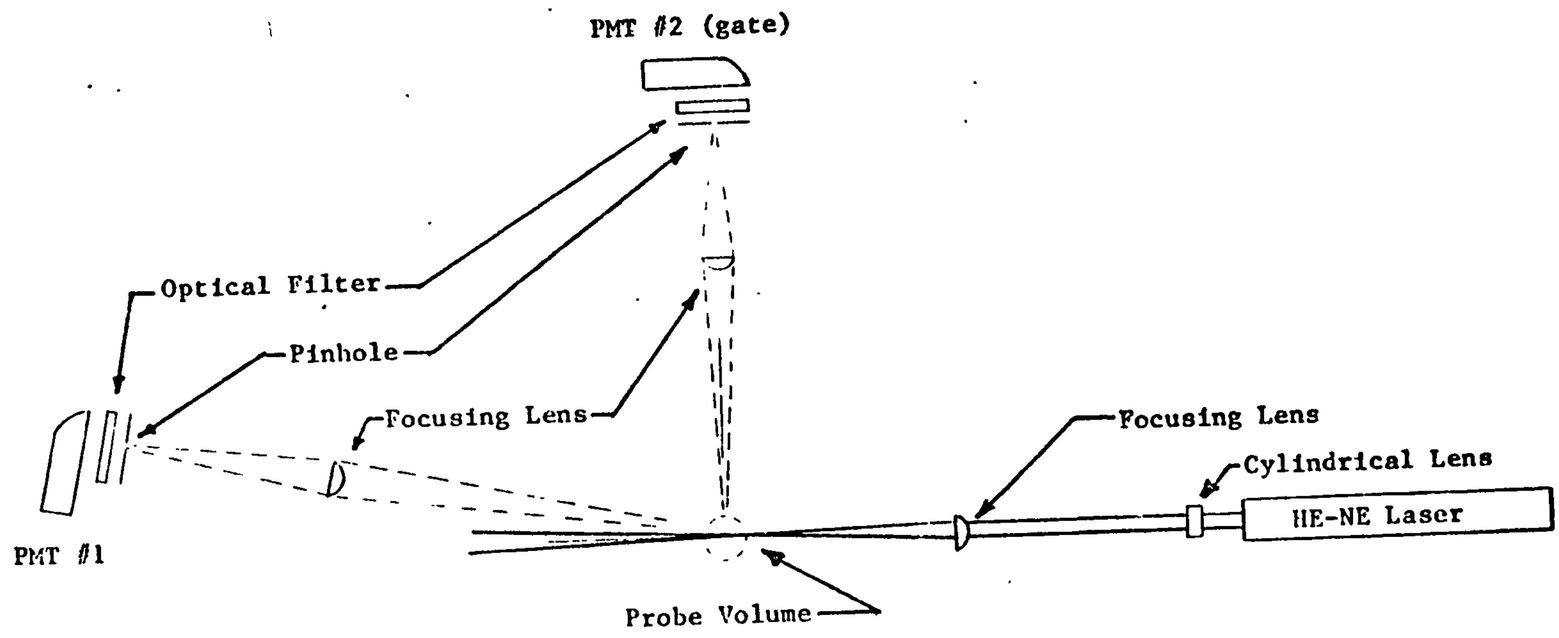

FIGURE 3. OPTICAL ARRANGEMENT FOR DROPLET SIZING

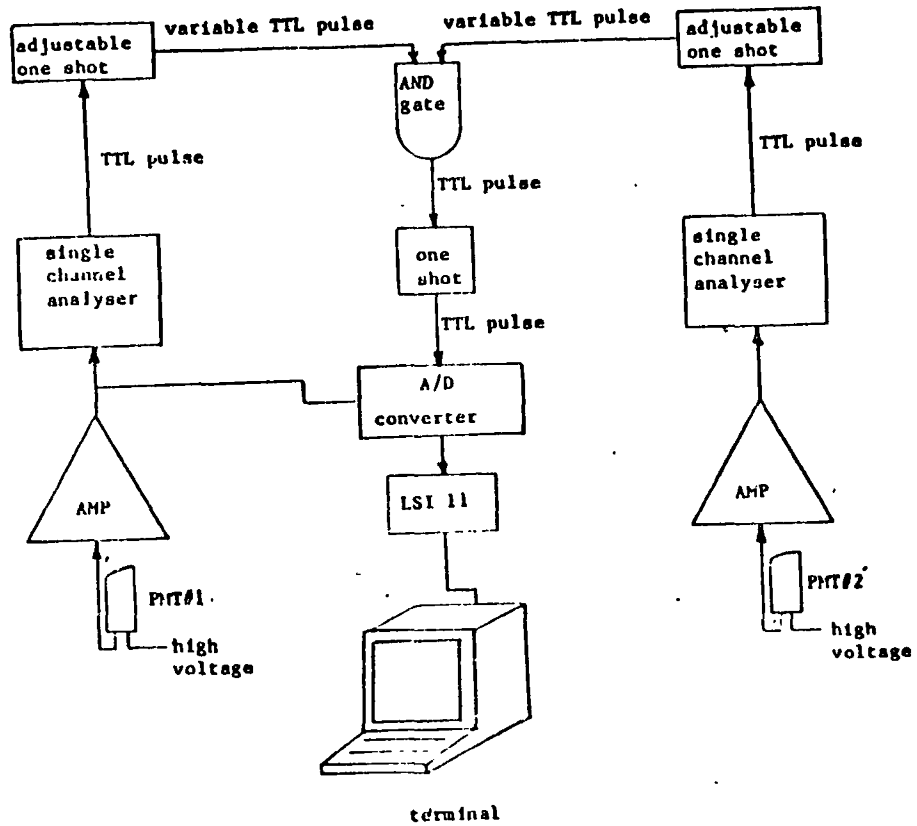

FIGURE 4. SCHEMATIC OF SIGNAL PROCESSING SYSTEM FOR LASER DROPLET SIZING APPRATUS.

produces a variable-width TTL-logic pulse. The output from the two adjustable one shot chips are compared in an "and" gate. When these pulses overlap in time, the "and" gate outputs another TTL-logic pulse which triggers an analog-to-digital conversion of the primary signal detector output by the A/D converter of the LSI 11/2 based minicomputer. The data can then be stored on disk and later analyzed to obtain the droplet size distribution. A delay exists from the time the peak in the signal occurs until the signal is actually read by the A/D converter. This is due to the processing in the SCA and is of the order of one microsecond. Since the signal generated by the droplet is expected to have a width of about 100 microseconds (100 μm/1 m/sec) there will only be a slight error in measuring peak height with this apparatus. An estimate of the error in the peak height voltage, V(0), can be made by noting that the voltage V(t) measured at a time δt after the peak occurs is

$$V(\delta t) \simeq V(0) + \ddot{V}(0)\,\frac{\delta t^2}{2}$$

For a Gaussian signal

$$V = \frac{1}{\sqrt{2\pi}\,\sigma}\ \exp\,[-t^2/2\sigma^2]$$

and

$$\ddot{V}(0) = -V(0)/\sigma^2.$$

Therefore

$$\frac{V(0) - V(\delta t)}{V(0)} \simeq \frac{1}{2}\left(\frac{\delta t}{\sigma}\right)^2.$$

If δt is 1 μS and σ is about 25 uS the error in peak voltage measurement is 0.08% which is adequate for this experiment.

C. Future Work

Work will begin shortly on the determination of the burning characteristics of sprays in the transition region. Parametric studies of the effects of droplet size, equivalence ratio, number density, prevaporization, flow velocity, and fuel and oxidizer composition on minimum ignition energy and flammability limits will be made as soon as the exploratory tests of the modified burner apparatus and new ignition system have been completed. Subsequent studies will be conducted to determine flame speed behavior with changing droplet size, size distribution, evaporation environment, etc. In short, progress will continue as indicated in the program plan, Table 1.

III. SUMMARY

A program was initiated in January, 1983 to study the true droplet size effects on burning velocity, minimum ignition energy, and the extension of the flammability limits in the transition region (10-80 μm droplet diameter) for liquid fuel sprays. The work follows a similar study of NO_x formation in the transition region for fuel sprays which was completed in 1983.

An existing fuel spray apparatus, which uses a Berglund-Liu monodisperse droplet generator is being used with appropriate additions and modifications for the present experimental program. In particular, the spray burner has been converted to a downward flowing configuration and the flow geometry has been altered to improve the burner operating characteristics. An ignition system with the capability to vary spark energy and duration independently has been designed and fabricated. This will allow the precise determination of the minimum ignition energies. An in-situ optical droplet sizing apparatus utilizing near forward Mie scattering of a He-Ne laser beam by the droplet stream has been designed and assembled. This technique uses a gate detector to insure that only those droplets passing through the center portion of the beam will be sized, thus eliminating the need for complicated signal processing used in other optical droplet sizers. This technique provides for droplet sizing in the range of approximately 10 to 100 μm. It is also a non-intrusive size measurement with a minimal dependence on index of refraction. The use of the same experimental apparatus for all of the measurements described above is expected to result in a uniform interpretation of the data that has not existed previously.

Experiments to characterize the ignition behavior of a model fuel at selected operating conditions have begun. Optimum spark gaps which result in minimum ignition energies at these conditions are being determined. Following these exploratory tests, parametric studies of the effects of droplet size, equivalence ratio, droplet number density, prevaporization, flow velocity, and fuel and oxidizer composition on minimum ignition energy and flammability limits will be performed. Subsequent studies of the same variables and their effects on flame speed will be conducted in the latter stages of the program.

IV. RESEARCH PERSONNEL

Professors Nicholas P. Cernansky and Izak Namer as Co-Principal Investigators provide coordination for this research program. They share overall responsibility for conducting, directing, and reporting the various phases of the research program. In addition, Mr. Robert J. Tidona as staff Research Engineer has been responsible for the development of new experimental techniques in conjunction with Professors Cernansky and Namer. Mr. Hamid Sarv (Ph.D. Candidate) has been involved with experimental and analytical details of the project. Mr. Shawn Smolsky (Drexel Research Co-op) has assisted in the details of the design of the ignition system.

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